The sequential development of magmatic and ore-forming processes in the Fundsjø Group, Meråker district, Central Norway

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Regional setting

The metavolcanic Fundsjø Group is situated in the eastern part of the Trondheim Nappe Complex, equivalent to the Köli part of the Upper Allochthon of the Scandinavian Caledonides (Gee et al. 1985). Although the subduction affinity (Grenne & Lagerblad 1985, Grenne 1987) of the Fundsjø Group is now generally accepted, various models have been suggested for its exact paleogeographic setting. Stephens & Gee (1989) suggested an oceanic setting on the Laurentian side of Iapetus, whereas a paleogeographic linkage to the Baltoscandian continent has been proposed by, e.g., Roberts et al. (1985).

The regional setting of the Fundsjø Group resembles strongly that of the Stekenjokk metavolcanites (Stephens 1986) further north in the Swedish Caledonides. The two units are comparable in age (c. 490 Ma) and both are structurally overlain by a sequence dominated by metapelites which are partly graphitic and contain interlayers of quartzite and quartzite conglomerate as well as thin limestones and metabasalts. Furthermore, both are structurally underlain and stratigraphically overlain by calcareous phyllites which contain gabbroic intrusions and local metabasaltic units.

The Fundsjø–Stekenjokk metavolcanite sequence has a combined strike length of more than 450 km and is one of the most important 'greenstone belts' in the Caledonides in view of the high abundance of massive volcanogenic sulphide (VMS) deposits. The biggest deposit is the Stekenjokk-Levi orebody containing originally c. 26 million metric tons (Mt) of ore.

The Meråker area

The general geology of the Meråker area (Fig. 1) has previously been outlined by Wolff et al. (1967) and Wolff (1973). The present account is based on studies of key profiles and localities combined with airborne geophysical data obtained during a mineral resource reconnaissance programme carried out by NGU.

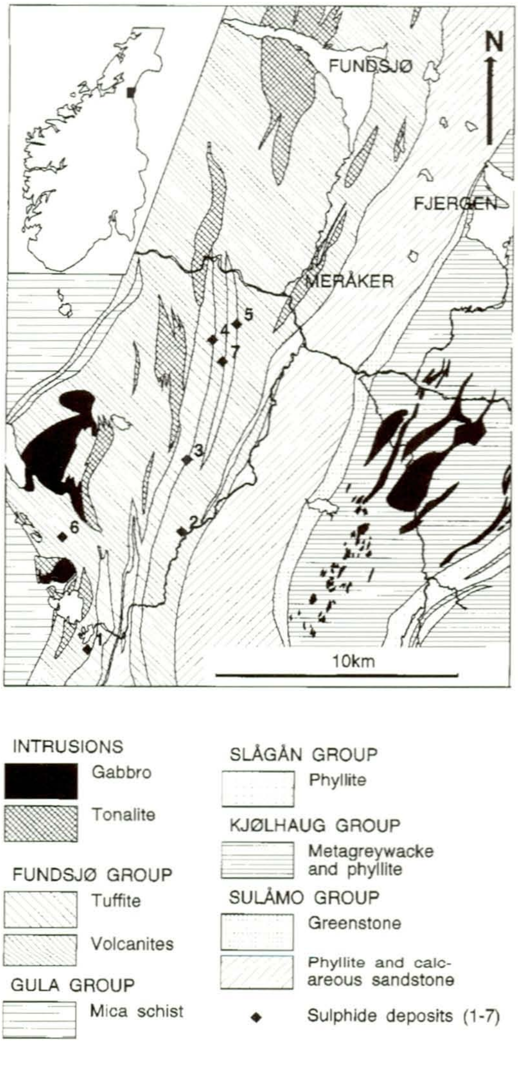

Fig. 1. Simplified geological map of the Meråker area. Volcanogenic sulphide deposits are indicated by numbers: 1: Kongens, 2: Torsbjørk, 3: Mannfjell, 4: Øytrø, 5: Fonnfjell, 6: Skrøydalen, 7: Løvlibekk.

The 7-9 km thick Fundsjø Group is structurally overlain, with a steep west-dipping contact, by metasediments of the Gula Group. The Fundsjø and Gula Groups were both involved in two phases of early isoclinal folding, which is not seen in the younger sedimentary formations to the east (Lagerblad 1983). This deformation, of Early Ordovician age, effectively masked primary structures of the less competent lithologies such as volcanic and volcaniclastic rocks, except in certain local areas. Metamorphic grade ranges from high amphibolite to greenschist facies.

The Sulåmo Group to the east is lying stratigraphically above the Fundsjø Group, and contains at its base a local conglomerate (Lille Fundsjø Conglomerate; cf. Wolff et al. 1967) composed of detritus from the underlying deformed igneous complex. The conglomerate is followed up sequence by phyllites and calcareous sandstones and a metabasaltic unit. Gabbro bodies associated with swarms of plagioclase-phyric metadolerite dykes occupy large portions of the Fundsjø Group and are also found locally in the Gula and Sulåmo Groups. The intrusions post-date the early isoclinal folding of the Fundsjø and Gula (Grenne & Lagerblad 1985).

Fundsjø Group stratigraphy

The lower part of the Fundsjø Group stratigraphy is a sequence of basaltic volcanites and co-magmatic dykes and subordinate gabbro. Pillow lava, pillow breccia and hyaloclastites are preserved locally and imply a submarine origin. A thin iron-formation comprising alternating layers of magnetite, pyrite and quartz occurs locally within the basaltic pile.

The basaltic sequence is intruded by a suite of coarse-grained tonalitic rocks; these are most extensively developed in the northern part of the area (Fig. 1) where they form bodies up to 3 km across and at least 15 km long. Acidic dykes are numerous above the larger intrusions and in places comprise quartz-feldspar phyric varieties. Overlying the tonalite-intruded basaltic sequence is a level of acidic volcanites which are mineralogically and texturally similar to the acidic dykes. Their effusive origin is revealed by local fine lamination and their conformable nature; however, their precise origin either as tuffs or flows, or both, has not been possible to define due to deformation and metamorphic recrystallisation.

The acidic volcanites are overlain by a variably thick sequence of layered tuffitic sediments with local interlayered pillow lavas and acidic pyroclastic rocks compositionally similar to those below. The tuffites are generally fine grained and display a compositional banding due to varying proportions of acidic and basic detritus; graphitic varieties are quite common and locally pass into graphite schist. Graphite is most abundant to the south where the tuffitic sequence attains its greatest thickness, and disappears towards the north accompanied by a gradual thinning out of the tuffites.

Deposit no.	1	2	3	4	5	6	7
Cu %	1,4	3,0	1,1	1,0	2,1	1,3	2,4
Zn %	5,0	0,9	5,0	10,0	6,3	0,2	0,2
Pb ppm	35	80	473	3695	113	8	13
Ag ppm	6	14	36	90	8	4	16
Au ppm	0,1	0,1	0,9	1,9	0,2	0,1	1,1
As ppm	5	41	80	3050	11	14	4

Table 1. Bulk composition of VMS deposits in the Meråker district. Stratiform massive sulphides: no. 1-5, feeder-type deposits: no. 6-7. Deposit numbers refer to Fig. 1.

VMS deposits

Massive stratiform sulphides in the Meråker area are generally confined to the acidic volcanite level but also occur within the tuffitic sequence. Most deposits are proximal, being situated directly above hydrothermal feeder conduits in the form of stockwork, stringer or disseminated pyrite-pyrrhotite-chalcopyrite mineralisation with a high Cu/Zn ratio and very low Pb contents. Stockwork mineralisation with no spatial relationship to known stratiform sulphides (Table 1, no. 6-7) is thought to represent feeder conduits to presently unexposed ores.

The actual massive stratiform deposits are generally situated between the acidic effusive rocks and the overlying tuffites. The most important of the known deposits are clustered in the central-southern part of the area. They form sheet-like bodies with thicknesses usually not exceeding 1 metre, and are dominated by pyrite and sphalerite; chalcopyrite, pyrrhotite, galena and arsenopyrite occur in variable proportions. Bulk compositions (Table 1) of massive ore indicate a tendency towards increasing Zn, Pb, Au, Ag and As values from south to north.

Geochemistry

Preliminary interpretations of geochemical data from the Meråker area indicate that the igneous rocks of the Fundsjø Group can be subdivided into well-defined types which are represented by analyses shown in Fig. 2. The oldest basalts recorded have a composition which is indistinguishable from typical mid-ocean ridge basalts (MORB) with the exception of a pronounced negative Ta anomaly. Such anomalies are a distinctive feature of island arc-related magmas (Saunders & Tarney 1984), and lavas comparable to the *MORB-like* basalts from the Fundsjø Group have been found in the Lau Basin (Vallier et al. 1991).

In the upper part of the basaltic sequence, possibly following deposition of the thin iron-formation, the *MORB-like* basalts were succeeded by low-K tholeiitic basalts which have a signature comparable to that of modern island arc tholeiites (IAT), such as low contents of most high field strength elements and a high Th/Ta ratio.

The acidic effusive rocks are geochemically identical to the large tonalitic intrusions and dykes, and represent a consanguineous suite of acidic melts which were erupted subsequent to the *IAT-type* volcanic period and at intervals during deposition of the tuffitic sequence. The rocks are very low in potassium and other large-ionic lithophile elements (LILE), a feature which must be largely primary since the LILE contents are uniformly low in the volcanic as well as in the various intrusive equivalents. They classify as low-K rhyolitic melts, and are very similar to acidic rocks formed in nascent back-arc basins in the Izu-Ogasawara arc (Ikeda & Yuasa 1989). Their low content of incompatible trace elements and distinctive REE pattern (Fig. 2) argue strongly against a derivation from the basaltic magmas by crystal fractionation; an origin by partial melting of basaltic material under hydrous conditions (Helz 1976) is more likely.

A third group of basaltic lavas occurs above the first acidic volcanites and is seemingly pene-contemporaneous with, or succeeded by, low-K rhyolitic magmatism recorded by local tuffs within the volcaniclastic sequence. These basalts are characterised by very strong HFSE-depletion but with an 'arc-type' Th/Ta signature similar to that of the preceding basalt types. The REE pattern (Fig.2B) of these *depleted IAT-type* basalts is distinctly different from that of the underlying *IAT-type* basalts, denoting that they represent different parent magmas and are not related by crystal fractionation processes.

Conclusions

Preliminary interpretations of data from the Meråker area indicate the following sequential development of the Fundsjø Group, schematically illustrated in Fig. 3:

1. Accumulation of a thick submarine sequence of *MORB-like* basalts, followed by deposition of ferruginous cherty sediments.
2. Continued basaltic submarine volcanism of *IAT-type* composition.
3. Introduction of large volumes of low-K rhyolitic melts to the basaltic crust in local intrusive centres, generated by partial melting of hydrated basic crust at deeper levels.
4. Uplift of oceanic crust related to the acidic intrusions, locally to subaerial levels with exposure of older basaltic material to erosion processes.
5. Eruption of low-K rhyolitic melts and deposition of water-lain tuffs and possibly flows.
6. Convective hydrothermal activity in the crust induced and driven by heat from the acidic intrusions, with precipitation of VMS deposits from

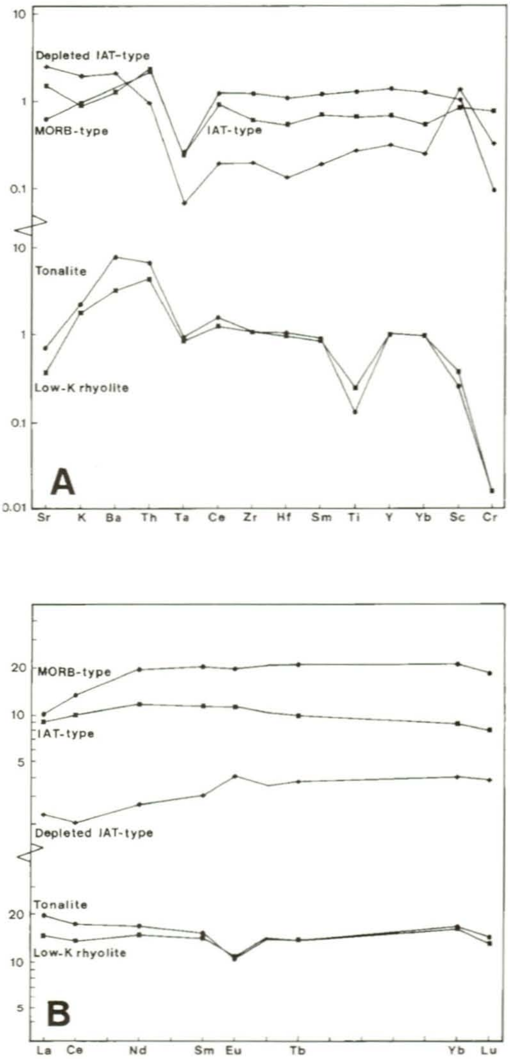

Fig. 2. MORB-normalised spidergrams (A) and chondrite-normalised REE plots (B) of representative samples of different igneous rock-types from the Fundsjø Group referred to in the text. Sr, K, Ba, Zr, Ti and Y analysed by XRF at NGU. REE and Th, Ta, Hf and Sc analysed by Instrumental Neutron Activation at University of Leuven, Belgium.

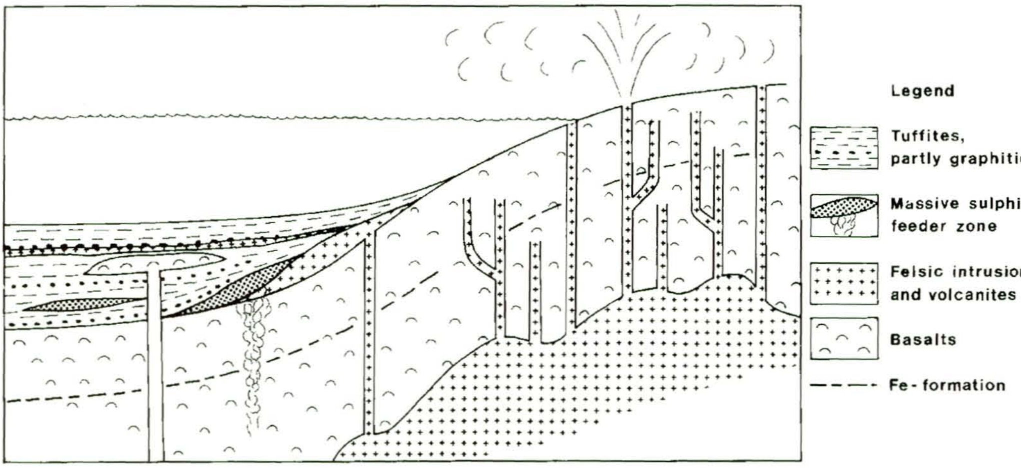

Fig. 3. Schematic model for the igneous and metallogenic development of the Fundsjø Group in the Meråker area.

the ascending hydrothermal solutions at the seafloor. VMS formation largely controlled by, and confined to subaqueous regions around acidic magmatic centres, leading to the observed clustering of deposits in a segment of the Fundsjø Group where the tuffitic sequence wedges out northwards towards a supposed acidic intrusive centre (see also Fig. 1).

7. Erosion of basic and acidic volcanic material from subaerial regions with deposition of mixed tuffites in partly euxinic basins between the acidic centres.

8. Local eruptions of *depleted IAT* basalts, and waning acidic volcanism and VMS-forming hydrothermal activity, contemporaneous with continued deposition of tuffites.

No sign of the vast, arc- or back-arc type magmatism of the Fundsjø Group is seen in the adjoining Gula Group, indicating that a major tectonic break exists between the two. It is likely that the Fundsjø and Gula complexes were amalgamated prior to an early tectonic event, probably in Early Ordovician times, since they both suffered a similar type of isoclinal folding prior to deposition of the overlying sediments of the Sulåmo Group.

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